

Thermal Development of the Mars 2020 Enhanced Engineering Cameras

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The engineering cameras (ECAMs) of the 2003 Mars Exploration Rover (MER) mission were re-flown on the Mars Science Laboratory (MSL) mission that launched in 2011. The upcoming Mars 2020 rover mission will introduce a new fleet of cameras called the enhanced engineering cameras (EECAMs). These EECAMs will have improved imaging capability, as the technology of the past ECAMs flown on Mars surface missions have become outdated. The EECAMs include six upgraded HazCams, two upgraded NavCams, and a single, newly-conceived CacheCam. The purposes of the HazCams and NavCams remain the same as they were for MER and MSL: to detect hazards to the front and rear of the rover, and to help in navigation across the Martian surface. The CacheCam will be used to take images of samples obtained by the rover's Sample Caching System. This paper compares the differences in the thermal designs of the ECAMs and EECAMs, their design drivers, and their implications for the mission operations of the Mars 2020 rover.

Nomenclature

α	=	Solar Absorptivity
ε	=	Infrared Emissivity
<i>AFT</i>	=	Allowable Flight Temperature
<i>AU</i>	=	Astronomical Unit
<i>BOL</i>	=	Beginning-of-Life
<i>CacheCam</i>	=	Sample Caching Camera
<i>CCD</i>	=	Charge-Coupled Device
<i>ChemCam</i>	=	Chemistry and Camera Instrument
<i>CMOS</i>	=	Complementary Metal-Oxide-Semiconductor
<i>DDR</i>	=	Detailed Design Review
<i>ECAM</i>	=	Engineering Camera
<i>EECAM</i>	=	Enhanced Engineering Camera
<i>EOL</i>	=	End-of-Life
<i>FSW</i>	=	Flight Software
<i>HazCam</i>	=	Hazard Avoidance Camera
L_s	=	Solar Longitude
<i>LSW</i>	=	Landing Site Workshop
<i>Mastcam</i>	=	Mast Camera
<i>MAHLI</i>	=	Mars Hand Lens Imager
<i>MER</i>	=	Mars Exploration Rover
<i>MMRTG</i>	=	Multi-Mission Radioisotope Thermoelectric Generator
<i>MSL</i>	=	Mars Science Laboratory

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<i>NavCam</i>	= Navigation Camera
<i>NASA</i>	= National Aeronautics and Space Administration
<i>NTE</i>	= Not-to-Exceed
<i>PRT</i>	= Platinum Resistance Thermometer
<i>PCB</i>	= Printed Circuit Board
<i>RA</i>	= Robotic Arm
<i>RPAM</i>	= Rover Power and Analog Module
<i>RSM</i>	= Remote Sensing Mast
<i>SCS</i>	= Sample Caching System
<i>SHA</i>	= Sample Handling Arm
<i>WCC</i>	= Worst-Case Cold
<i>WCH</i>	= Worst-Case Hot

I. Introduction

The Mars 2020 rover, which is scheduled to launch in July 2020, will be one of NASA's latest endeavors into the robotic exploration of the Martian surface and its geologic history. The Mars 2020 project is being designed and built at the Jet Propulsion Laboratory (JPL) of the California Institute of Technology (Caltech) in Pasadena, CA. Akin to the Curiosity rover of the Mars Science Laboratory (MSL) mission that launched in 2011, one of the Mars 2020 rover's primary goals will be to search for conditions that can or once could sustain life. Building on the work done by Curiosity, this newer rover will also seek for signs of ancient microbial life. To help aid in this effort, the rover will have a newly designed Sample Caching System (SCS) that can excavate rock samples, store them in sample tubes, and deposit them on the ground for potential future return. The purpose behind this is to allow scientists on Earth to better analyze the samples in ways that cannot be done in-situ. The Mars 2020 project is aiming to have as much of its design be build-to-print, recycling most of the architecture from MSL to save on cost and reduce the mission risk. The engineering cameras of the Mars 2020 rover, however, are one of the few technologies that will not be build-to-print and are undergoing a complete re-design. These Mars 2020 cameras have their own subsystem and development team, while the optics assemblies are contracted out to an external vendor. The thermal design and analysis of both the cameras and optics is done by the Mars 2020 Flight System Thermal Team, except for the board-level thermal design and analysis, which is done by the EECAM development team.

II. Overview of MSL Engineering Cameras and Mars 2020 Enhanced Engineering Cameras

A. Overview of MSL Engineering Cameras

Although there are typically several cameras that fly on each Mars surface mission, the *engineering* cameras (ECAMs) are a particular subset of cameras that are primarily used for rover guidance, navigation, and control. In contrast, cameras such as the ChemCam (Chemistry and Camera Instrument, MSL) or MAHLI (Mars Hand Lens Imager, MSL) are considered science instruments, as they are primarily used for scientific objectives and not spacecraft operations.

The first generation of ECAMs were originally developed for use on the Spirit and Opportunity rovers of the Mars Exploration Rover (MER) mission. There were a total of six ECAMs per rover: four Hazard Avoidance Cameras (HazCams) and two Navigation Cameras (NavCams). An additional camera, the Descent Camera, was also designated as an engineering camera on MER. However, it was only used during the landing sequence of the rover and not for any surface operations.¹ The six surface MER ECAMs were reused on MSL with the same exact design, except in larger quantities and slightly higher heater powers. On MSL, there were a total of 12 ECAMs: eight HazCams and four NavCams. Their locations on the Curiosity rover are shown in Figure 1.

Four of the MSL HazCams were located at the front of the rover beneath the Robotic Arm (RA) and the other four were located at the rear of the rover, in pairs on either side of the MMRTG (Multi-Mission Radioisotope Thermoelectric Generator). The primary purpose of the HazCams was to provide stereo imaging of the environment that could be used to detect hazardous obstacles directly to the front and rear of the rover while traversing the Martian terrain. Secondary purposes of the HazCam included: supporting RA and turret activities, examining the wheels, and assisting in the attitude determination of the rover. The MSL HazCams operated as stereo pairs, with two front HazCam stereo pairs and two rear HazCam stereo pairs. The redundancy of the stereo pairs was meant as a contingency plan to reduce mission risk: in the event of a camera failure in one of the stereo pairs, the redundant pair could be used instead to maintain mission operations.

The four MSL NavCams were located at the base of the Remote Sensing Mast (RSM) head, with each pair of cameras on either side of the Mastcam (Mast Camera). The primary purpose of the NavCams was also to provide stereo imaging of the Martian terrain (except over longer distances than the HazCams) as well panoramic images of the rover's surroundings. The secondary purposes of the NavCams were identical to those of the HazCams. These two ECAM types worked in conjunction to assist in the autonomous operation of the rover. As with the HazCams, the NavCams also operated in stereo pairs, with two stereo pairs for the same redundancy as the HazCams.

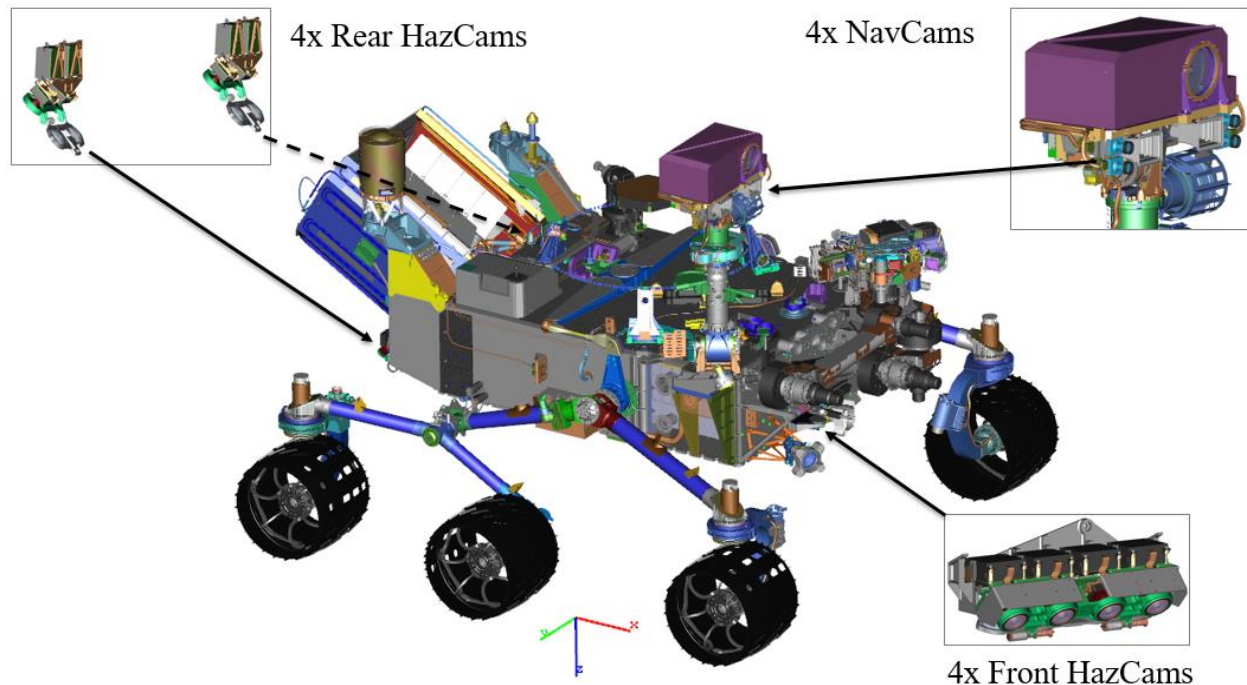


Figure 1 – Locations and Quantities of MSL ECAMs

The NavCams and HazCams were nearly identical in architecture. Both cameras had identical housings and differed only by their lens designs, with the HazCam lens being the more massive with a smaller focal length and larger field of view. The housing of the ECAMs was a two-box design: one box for the optical components (lens assembly and detector) and the other box for the camera electronics. The boxes were connected together by a flex cable. The detector that was used in the ECAMs was a CCD (charge-coupled device) that imaged in black and white with a resolution of 1024 x 1024 pixels. The warm-up heaters used on the MSL ECAMs were in the form of chip resistors at the board-level of the electronics, with a total power of 3.5 W. The operational power of the ECAMs was 2.75 W. As part of the mission program, a total of 26 ECAMs were built. Although only 12 actually flew on the mission, four were built as flight spares and 10 were built as engineering units.² The ECAM architecture is shown in Figure 2.

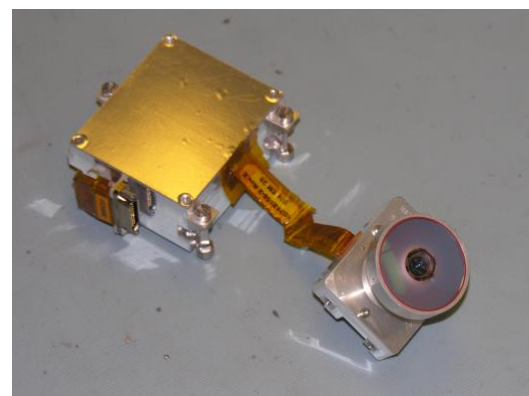


Figure 2 – MSL ECAM

B. Overview of Mars 2020 Enhanced Engineering Cameras

As aforementioned, the MSL ECAMs were heritage hardware that was build-to-print from the 2003 MER mission. As that same technology is now well over a decade old and obsolete, the Mars 2020 mission program is introducing a new, more powerful camera called the *enhanced* engineering camera (EECAM). Nine EECAMs will fly on the Mars 2020 rover: six enhanced HazCams, two enhanced NavCams, and a newly designed engineering camera, the CacheCam (Sample Caching Camera). As with the MSL ECAMs, the architecture across the different

Mars 2020 EECAM types differ only by their lens designs – their housings are completely identical (with the exception of the thermal-optical coatings). This uniformity makes the implementation of the designs less complex and, in some ways, lower risk. Their locations on the Mars 2020 rover are shown in Figure 3.

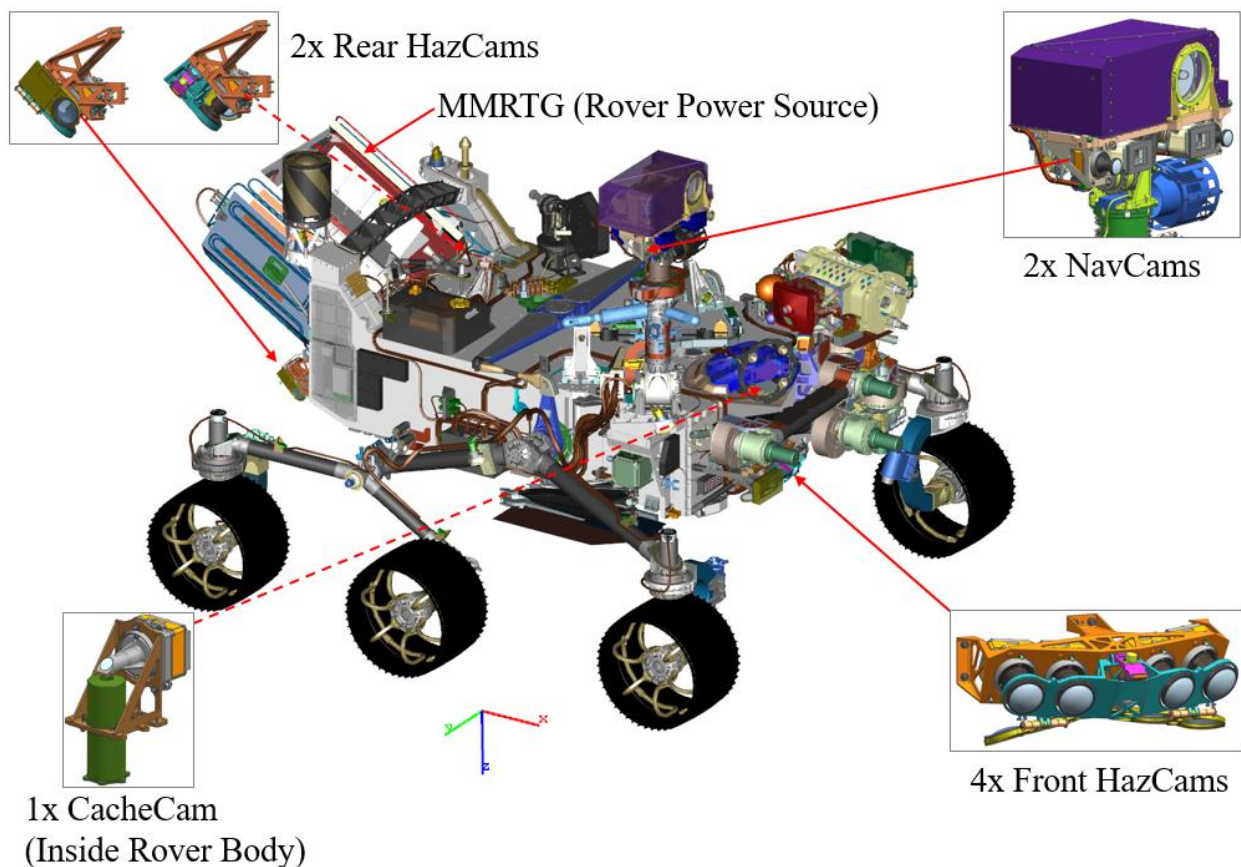


Figure 3 – Locations and Quantities of Mars 2020 EECAMs

As with the previous generation of engineering cameras of the MSL rover, the Mars 2020 HazCams are located on the front rover chassis and rear panel of the rover. The number of front HazCams has stayed the same, but the number of rear HazCams has decreased from four to two. The functional requirements of the HazCams have not changed; their purpose is to aid in the mobility and operations of the rover.

Similarly, the locations and objectives of the Mars 2020 NavCams have not changed since MSL. They are also located on the RSM head (which is build-to-print from the MSL RSM) and their primary objective is once again to obtain stereo and panoramic imaging for aiding in the rover's day-to-day operations. As with the rear HazCams, the total number of NavCams has decreased from four to two.

The single CacheCam (shown in Figure 4) is part of the rover's newly developed SCS located inside the ACA (Adaptive Caching Assembly), and is mounted to the CCMD (Caching Component Mounting Deck). The ACA is located towards the front of the rover, behind the front chassis panel and beneath the top deck. The purpose of the CacheCam is to take monoscopic images of any samples obtained by the SCS. As such, the CacheCam is unique compared to other engineering cameras of the current and past rovers. Additionally, the CacheCam operates in a very different manner than the other cameras. It functions similarly to a periscope in a submarine. Once a sample is retrieved and stored in a sample tube, the sample handling arm (SHA) inserts the tube into the lens baffle. An illuminator is mounted onto the end of the lens and shines light down the lens baffle to illuminate the sample tube. The end of the lens contains a fully-silvered mirror so that incoming light from the sample tube can be redirected 90° and enter the detector inside the camera housing.

The reduction in the number of rear HazCams and NavCams is primarily due to a significant design shift of the EECAMs from the original ECAM paradigm. The ECAM design had two housings – one for the optical components and the other for camera electronics. The EECAM design has merged these two housings into one singular housing

containing all aspects of the camera, upon which the lens assembly is mounted. The driver behind this is the change to a CMOS (complementary metal-oxide-semiconductor) detector that can image in color with a 5120 x 3840 pixel resolution, a significant improvement from the CCD detector of the ECAMs.³ To accommodate this much more capable (and thus, much larger) detector, as well as the electronics to support it, the housings had to increase in size and eventually merged together. This shift to a single-housing design has increased the overall volume of the EECAM compared to the ECAM, effectively reducing the number of cameras that could fit within the allocated NTE (Not-to-Exceed) volume on the rover. Furthermore, although only nine EECAMs will fly on the mission, there are many more that need to be built for qualification, engineering development, and flight spare kits. Decreasing the total number of cameras that will need to fly means fewer units need to be built, thus lowering overall costs and the risk of implementation. In fact, there are 25 total units that will be built (comparable to 26 units built on MSL): nine units as part of the flight kit, four units for the flight spare kit, three qualification units, and nine engineering units. However, due to the decrease in the total number of cameras, there are no longer any redundant rear HazCam and redundant NavCam stereo pairs. The project has accepted the increased risk in this area. The warm-up heaters used on the EECAMs have a power of 20 W, and the operational power dissipation of the cameras is 2.22 W.

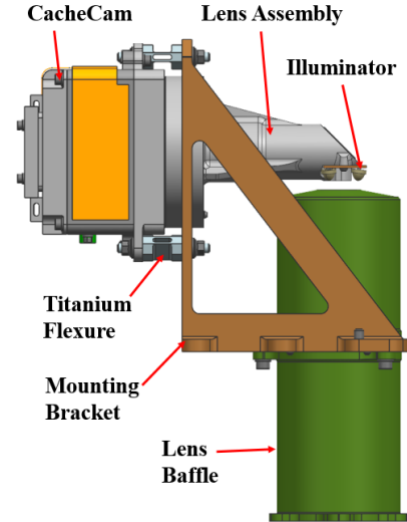


Figure 4 – CacheCam Installation

III. Thermal Design of Mars 2020 EECAMs

A. Environmental Factors and Assumptions

The difficulty in the thermal design for Mars surface missions lies in the extremities of the Martian environment, which is highly dependent on the landing site of the mission (specifically the latitude of the landing site). Due to the eccentricity of Mars' orbit ($\epsilon = 0.0934$) and axial tilt (25°), southernly landing sites experience hotter summers and colder winters rather than northernly landing sites. During the Martian summer, the southern hemisphere is tilted towards the sun and Mars is at its perihelion (closest point in its orbit from the sun). Alternatively, during the Martian winter, the southern hemisphere is tilted away from the sun and Mars is at its aphelion (furthest point in its orbit from the sun). Furthermore, since Mars' distance from the sun is anywhere between 1.38 and 1.67 AU (Astronomical Units), the incident solar flux is much less on the surface of Mars than it is on Earth. This makes the thermal design for the WCC operation of the rover (and consequently, the cameras) much more arduous.

The landing site of the Mars 2020 rover has not yet been finalized. At the time the EECAM thermal design was being developed, there were a total of eight options that were in the running. Of those eight landing sites, Holden Crater (26°S) held the greatest thermal extremes. As such, Holden Crater is the environment around which the Mars 2020 thermal design had been developed. However, a recent Landing Site Workshop (LSW) in February 2017 resulted in the downselect of the landing site options to three final candidates: Jezero Crater (18.5°N), NE Syrtis (17.8°N), and Columbia Hills (15°S).⁴ The new worst-case environment, Columbia Hills, is nearly identical to Holden Crater. As such, the thermal performance won't be significantly different once the analysis is updated to reflect the Columbia Hills environment. Furthermore, designing to the WCC and WCH (worst-case hot) landing site ensures the most robust thermal design. The Curiosity rover landed in Gale Crater (4.5°S), which had a much more benign thermal environment than the current worst-case candidate for Mars 2020.

The design philosophy at JPL is to stack WCC and WCH assumptions when developing a thermal design, with the rationale that the conservatism in this approach leads to a more robust and versatile thermal design. In a WCC analysis, there are a few key assumptions that are made. Firstly, as aforementioned, analysis of the EECAMs was done assuming a Holden Crater environment. Specifically, the WCC analysis is done assuming winter at Holden Crater with a solar longitude of $L_s = 91^\circ$. Typical wind speeds on the surface of Mars range between 0 m/sec and 15 m/sec. Based on meteorological data from the Viking 1 and 2 landers, although those missions did experience maximum wind speeds of up to 30 m/sec, the wind speeds were 15 m/sec or less 99% of the time.⁵ Therefore, to avoid overconstraining the design, only a maximum speed of 15 m/sec is assumed. The wind speed is a significant factor since it drives the convective heat losses during the WCC operation of the rover. Wind speed is particularly an issue for some of the EECAMs located on the exterior of the rover (HazCams on the front and rear of the rover, NavCams on the RSM). While the CacheCam is located inside the ACA enclosure, the ACA is left open to the environment through an opening at the bottom of the rover where an ejectable belly pan is removed. Therefore, it

too experiences convective heat losses to the environment. In a WCC analysis with warm-up heater operation beginning at 8:00 a.m. in the morning and ending at 6:00 p.m. in the evening, the wind speed is assumed to be 15 m/sec (forced convection) to maximize heat losses to the atmosphere and make sure that the heaters in use have the capability to bring the cameras up to an operating temperature. For a WCC analysis with heater operation beginning at night or early in the morning, a wind speed of 0 m/sec is assumed. The reason for this is that during nighttime the sky is the greatest heat sink, rather than the atmosphere.⁶ Thus, the lack of wind drives the minimum initial temperature at the start of warmup. At first, applying a 15 m/sec wind speed would end up warming the hardware in this case, but once the cameras are warmer than the ambient atmosphere temperature, wind will start to pull heat away. In addition to environmental factors, there are adjustments that are made to thermal-optical properties of external surface coatings of rover components exposed to the environment. Since much of the rover thermal design incorporates active thermal control (heaters, fluid loops, etc.) to aid in the WCC operation, most external surfaces are painted white to reflect as much of the incident solar load as possible in the WCH operation. The beginning-of-life (BOL) thermal-optical properties of white paint are typically a solar absorptivity of $\alpha = 0.15$ and an infrared emissivity of $\varepsilon = 0.9$. Therefore, in a WCC analysis, BOL optical properties of white paint are used to ensure minimal absorption of sunlight. The bus voltage of the rover is assumed to be a minimum nominal value of about 28 V, to minimize the amount of power that can be delivered to the camera heaters. The electrical resistance of the heater is determined using this 28 V bus voltage to be conservative for the required heater area. The camera is assumed to be non-operating until the warmup is complete.

In the WCH analysis of the EECAMs, the environment in use is summer at Holden Crater with a solar longitude of $L_s = 259^\circ$. For conservatism, the wind speed is assumed to be 0 m/sec (natural convection) to minimize the convective heat losses that would otherwise benefit the hot side operability. The average power dissipation of the EECAMs is 2.22 W (in comparison, the operating power of the MSL ECAMs was 2.75 W). The operational use cases of the EECAMs vary depending on camera type and location. The NavCams can be used for up to two hours at a time, during which the rover is driving in auto-navigation mode. On MSL, the front HazCams were used for the same potential two-hour duration as the NavCams to assist in driving, but the Mars 2020 front HazCams were developed with the goal that they would mostly be used to map the workspace immediately to the front of the rover. However, the analysis assumes the Mars 2020 front HazCams will be on for two hours as well to leave open the possibility of their use during driving. The Flight System Thermal Team was provided with conservative values for how long the rear HazCams and CacheCam would typically be used and added some extra margin in the analysis. For example, the rear HazCams will not be used for auto-navigational driving. They will typically be used for only two minutes at a time, but in the analysis it was assumed that they will be on for five minutes. Similarly, the CacheCam would typically be used for up to 10 minutes at a time, but the analysis assumed they will be on for 20 minutes. Additionally, the CacheCam illuminator dissipates a maximum power of 0.75 W. The illuminator is hardwired in conjunction with the CacheCam such that it will be operational for the same period of time as the CacheCam. Therefore, the 2.22 W power dissipation (plus 0.75 W for the CacheCam illuminator) is applied during the hottest time of day for each of the respective cameras and their given duration of operations. The bus voltage is assumed to be at its maximum value of 32.8 V. Regarding the thermal optical properties, there are some adjustments that are made to the external, white-painted surfaces. The Martian environment has a lot of dust which is kicked up during windy days that then gets deposited onto external rover surfaces. This dust, having an $\alpha = 0.7$, increases the absorptivity of white paint to an extent that depends on the percent dust coverage of the surface. From MER, it was observed that horizontal surfaces typically end up with about 40% dust coverage and vertical surfaces typically end up with about 10% dust coverage, with the 10% dust coverage being the typical amount which can electrostatically stick to a surface. This dust coverage means that WCH white paint optical properties are $\alpha = 0.4$ for 40% dust-covered surfaces and $\alpha = 0.25$ for 10% dust-covered surfaces. The ε of white-painted surfaces does not change with dust coverage because the dust particle size is much smaller than the infrared wavelengths.⁷ Since the NavCams are located on the RSM which can move and swivel around, all NavCam surfaces are treated as “vertical” surfaces in the sense that the greatest dust coverage will be about 10%; any excess dust will just fall off as the RSM moves.

The final parameter that affects the WCC and WCH analysis is the orientation of the rover with respect to the cardinal directions (north, south, east, and west). Just like on Earth, on Mars the sun rises in the east and sets in the west. For both the WCC and WCH analyses, the rover is oriented such that the camera installation(s) being modeled is facing west. This ensures that in the morning when the warmup begins, the respective installation is shadowed from the sun by the rover to remove the benefit of an incident solar load on the camera warmup. This orientation is also used in WCH because it ensures that the camera installation has the best view to the sun during the hottest time of day in the late afternoon. Although the solar flux is a significant factor, it is not the only WCH driver that needs to be taken into account when determining the orientation of the rover. While the solar flux does peak at noon, there is some lag in the environmental temperatures, as well as lags in the temperatures of the cameras. This lag is long

enough such that the hottest camera temperatures occur when the sun has passed its highest point in the sky. A sensitivity study was done to validate this assumption and see which of the directions (north, south, east, or west) result in the hottest temperatures – a westward direction did indeed end up being the worst case. So, when analyzing the front HazCams and NavCams, the front of the rover is oriented to the west. Similarly, the rear of the rover is oriented to the west when analyzing the rear HazCams. Furthermore, in the NavCam WCC and WCH analysis, the RSM head is tilted all the way backwards so that the NavCam boresights are pointing towards the sky. This is suitable for WCC since the sky is the greatest nighttime heat sink – pointing the RSM head towards the sky ensures that the NavCams will undergo the coldest possible soak over the Martian night. As for WCH, pointing towards the sky means that the NavCams will also have the best possible view to the sun. Although the RSM head does have the potential to track the sun, the required orientation for that does not quite guarantee maximum solar exposure on the lens and camera bodies. Additionally, since the rover is mobile, it technically has the capability to orient itself to follow the sun. While this may be a thermally worst-case scenario, such a movement would never actually be implemented during mission operations. Therefore, the RSM and rover body are assumed to be stationary. Lastly, the rover orientation does not impact the analysis of the CacheCam installation since it does not see any sunlight at all. Table 1 below summarizes some of these WCC and WCH assumptions.

Table 1 – WCC and WCH Assumptions for Mars 2020 EECAMs

	Worst Case Cold (WCC)	Worst Case Hot (WCH)
Landing Site	Holden Crater (26°S) Winter ($L_s = 91^\circ$)	Holden Crater (26°S) Summer ($L_s = 259^\circ$)
Wind Speed	0 m/sec or 15 m/sec	0 m/sec
Rover Configuration	<ul style="list-style-type: none"> Cameras facing west NavCams point towards sky 	<ul style="list-style-type: none"> Cameras facing west NavCams point towards sky
Optical Coating Degradation and % Dust Coverage	Beginning-of-Life (BOL) 0%	End-of-Life (EOL) 10% for Vertical and NavCam Surfaces 40% for Horizontal Surfaces
Bus Voltage	28V (minimum)	32.8V (maximum)
Camera Operation and Dissipation	Either: <ul style="list-style-type: none"> Always off Turned on after warmup 	2.22 W for each EECAM (+0.75W for CacheCam Illuminator) Analyzed Use Cases: Front Haz/NavCams – On 2 hours Rear HazCams – On 5 minutes CacheCam – On 20 minutes

B. Thermal Requirements

1. Operational Temperature Requirements

The temperature requirements of the MSL ECAMs were identical for both camera types (HazCams and NavCams). The camera head (CCD detector and optics assembly) had an operational allowable flight temperature (AFT) range of -128°C to 50°C and the electronics housing had an operational AFT range of -55°C to 50°C.

The temperature requirements of the Mars 2020 EECAMs are more complex. The camera body operational AFT ranges of all three EECAM types are once again identical to one another and equivalent to those of the MSL ECAMs: -55°C to 50°C. The lens assemblies (which are unique to each EECAM type) each have different temperature requirements. Their operational AFT ranges are -95°C to 40°C for the HazCam lens, -75°C to 30°C for the NavCam lens, and -80°C to 25°C for the CacheCam lens. Additionally, the operational AFT range for the CacheCam illuminator is -80°C to 50°C. As per JPL thermal design principles, although the thermal design must ensure that the AFT limits are not exceeded, the actual hardware must be qualified to operate over a much wider range than the AFT temperature limits. This range is known as the qualification temperature range. At JPL, thermal designs must have 20°C of margin between the maximum operational AFT and maximum qualification temperature, and 15°C between the minimum operational AFT and minimum qualification temperature. Therefore, although the thermal design must guarantee the AFT limits are not exceeded, the lenses actually have to be designed to operate within specification over the entire qualification range. For example, the operational qualification temperature limits (and thus, design limits) for the EECAM lenses are the following: -110°C to 60°C for the HazCam lens, -90°C to 50°C for the NavCam lens, and -95°C to 45°C for the CacheCam lens. The AFT limits for the camera body are

applied at the camera housing. However, since the Flight System Thermal Team is responsible for designing warmup heaters, the warmup of the internals of the camera body must be guaranteed as well.

The reason for the variations in the lens temperature limits across all the different cameras lies in the greater complexity of the optical designs of the EECAM lenses over the ECAM lenses, resulting from the requirement that the EECAM must have an improved optical performance over the ECAM. During the design process, the lenses are athermalized over a specific temperature range that the Flight System Thermal Team provides. Athermalization is a key part of an optical design process in which a lens is developed to have a stable optical performance over a range of temperatures. One of the most common ways athermalization is achieved is through material selection of the glass elements and lens housing. The key idea here is that the *magnitude* of that temperature range drives the difficulty in the athermalization process, not the nominal limits. The provided temperature range can shift up or down, but as long as the magnitude of the range isn't exceeded, the athermalization does not get any more difficult.

The initial range over which the lens assemblies needed to be athermalized was an operational qualification range of -70°C to 70°C (operational AFT range of -55°C to 50°C) to match that of the camera body. This qualification range has a magnitude of 140°C, which is already a very challenging range to design over. This initial range was selected because before a fully-detailed thermal model was complete, the lens designs had been externally contracted to vendors outside of JPL. Since the vendors required a temperature range over which to athermalize their designs, the initial 140°C range was provided as a starting point. In the meantime, a detailed thermal model of the cameras was developed to predict the temperatures that all the lens assemblies were expected to see. Although the vendor lens designs were still in progress, the lenses that were included in the thermal model were notional designs that had been developed at JPL. These lenses, although not actual designs from the vendors, were developed to meet the optical performance requirements of the cameras and the vendors were using them as a foundation for their own designs. Therefore, they provided a proper representation of what the vendors' designs would most likely consist of. An agreement was negotiated between the Flight System Thermal Team and the lens vendors in which the Thermal Team would provide updated temperature ranges based on the analysis done on the notional designs. These new ranges would then be rolled over into the vendors' lens development. In determining the new temperature ranges, the goal was to try and maintain the original magnitude design range. As mentioned, this range can be shifted without causing any additional design challenges. Results of this analysis showed that during warmup, the lenses experience a lag in temperature rise compared to that of the camera body. This was expected, since the heater is located on the camera housing, away from the lens assembly, and the thermal mass of the lenses is a significant factor. Furthermore, the lens assemblies extend out of the camera bodies and have relatively large surface areas. Akin to a thermal fin, this type of configuration increases the rate of heat loss to the environment by way of convection. Therefore, the minimum operational AFT values for the lens assemblies were established based on the minimum temperature of the lens assemblies once the camera body completed its warmup (with some margin included to account for any deviations of the vendor designs from the notional JPL designs). The qualification temperatures were then set accordingly. Additionally, variations in the lens temperature limits across the EECAM types is also attributed to the facts that the lenses (particularly their masses) are not identical and the various camera installations are located on different parts of the rover. For the NavCam and CacheCam lenses, the nominal temperature limits were shifted downwards from the initial -70°C to 70°C qualification limits but the 140°C magnitude qualification range was maintained. For the HazCam lenses, however, the magnitude range had to be expanded to 170°C. The MSL ECAM lens designs were not quite as intricate – there were fewer lens elements and the optical performance requirements were not as rigorous as they are for the Mars 2020 EECAM lenses. Consequently, they did not have to undergo this athermalization process, evident in the fact that the magnitude of their operational AFT range was 178°C. Table 2 below summarizes the various operational temperature limits of the EECAMs.

Table 2 – Mars 2020 EECAM Operational Temperature Limits

Camera	Component	Operational Allowable Flight Temperature, °C		Operational Qualification Temperature, °C	
		Minimum	Maximum	Minimum	Maximum
HazCam	Camera Body	-55	50	-70	70
	Lens Assembly	-95	40	-110	60
NavCam	Camera Body	-55	50	-70	70
	Lens Assembly	-75	30	-90	50
CacheCam	Camera Body	-55	50	-70	70
	Lens Assembly	-80	25	-95	45
	Illuminator	-80	50	-95	70

2. Mounting Interface Requirements

All of the EECAMs interface with the rover via mounting brackets. To limit the heat losses to the brackets during the warmup of the cameras, there are a few requirements that are set in place, as well as some design implementations. Firstly, the EECAMs are mounted to their respective brackets through three thermal isolators per camera. These isolators are titanium flexures as shown in Figure 4. There is a requirement, set in place by the Flight System Thermal Team, that the Rover Mechanical Team has to meet, which states that the total thermal resistance across those three thermal isolators has to be at least $14^{\circ}\text{C}/\text{W}$. As a starting point, this thermal resistance requirement was initially set based on the resistance values of existing isolator geometries that have flown on Mars surface missions in the past. As the mechanical designs of these interfaces matured, this requirement was re-negotiated between the Thermal and Mechanical Teams as necessary. If the proposed isolator design did not meet the resistance requirement, then the new resistance was evaluated in the thermal analysis. If the effects were acceptable, then a new resistance requirement was established.

Additionally, there is a requirement that states the minimum CO_2 gas gap between the cameras and any adjacent hardware (such as mounting brackets, other cameras, etc.) must be at least 4 mm. At small gaps, CO_2 gas conduction can be a significant contributor to heat losses. Therefore, these gas conductances are included in the thermal modeling of Mars surface missions. Any exceptions to this requirement are analyzed and approved on a case-by-case basis by the Flight System Thermal Team.

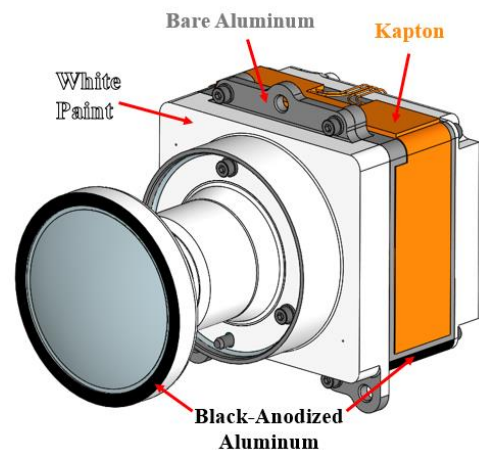
3. Operational Requirements

The Mars 2020 Flight System System Engineering Team (which is responsible for specifying requirements on the rover) has not placed any requirements on the warmup times, heater energy usage, or time of day of operations for the EECAMs, as it is not very straightforward to do so. In practice, however, if the Mars 2020 Operations Team finds that the “heat-to-use” practice is too energy-expensive, then the team would delay the start time of the cameras and begin heating later in the day, or employ a “wait-to-use” strategy to allow the environment to warm up the hardware. For some WCC environments, the “wait-to-use” strategy may not be sufficient to bring the cameras all the way up to their operating temperatures, but it can still be used to start the warmup from a more benign temperature. For some guidance, the Thermal Team did meet with the Flight System to determine how long of a warmup duration was an appropriate goal to have when developing warmup heaters. An agreement was made that a warmup time of an hour or less would be acceptable since that would not significantly affect mission operations, while a warmup time of ~30 minutes would be ideal to have. Thus, moving forward in the thermal development of the cameras, the Thermal Team made it a goal to have a warmup time of 30 minutes. No goals were set on the warmup energies of the cameras since the required warmup energies are significantly smaller than the warmup energies of some other rover hardware (such as the RA and mobility system).

C. Thermal-Optical Coatings

The major thermal-optical surface coatings of the HazCam are shown in Figure 5 to the right. To help the WCH performance of the cameras, there is white paint on the exterior of the lens assemblies and majority of the camera housing. There is also white paint on the HazCam mounting brackets (not shown in Figure 5). The heaters used are Kapton film heaters, which are applied to bare aluminum. The very end of the lens assembly is black anodized to prevent reflection off the white paint and into the optics assembly. The NavCam lens assembly, camera body, and mounting bracket surface coatings are identical to those of the HazCam.

While the NavCam surface coatings are identical to that of the HazCam, the CacheCam has different optical coatings. Since the CacheCam is located inside the ACA, which doesn’t see any sunlight, the white paint is unnecessary. Ideally, the CacheCam would still use white paint anyway so that the camera body would be interchangeable with the HazCam and NavCam camera bodies, but due to contamination requirements inside the ACA, this is not possible. The ACA is the primary region where the storage of rock samples obtained by the rover occurs. As such, there are stringent contamination requirements that forbid any organics inside of the ACA (unless absolutely necessary) because of the risk of contaminating the samples. Therefore, the areas on the CacheCam body where white paint would normally be are just bare aluminum instead,



**Figure 5 – EECAM (HazCam)
Surface Coatings**

and the exterior of the CacheCam lens assembly is black anodized. The CacheCam mounting bracket, made of titanium, is left as bare titanium.

D. Heater Design

The heater design approach that the Flight System Thermal Team utilizes is to place the largest heaters possible on hardware, as allowed by electrical current limits of switches and area constraints of hardware. This is done to heat the hardware as fast as possible so that there is more time for operations. As mentioned in Section II, the warmup heater of the MSL ECAMs was in the form of chip resistors on the printed circuit boards (PCBs) of the electronics box, totaling 3.5 W of power. One of the biggest thermal design changes from the ECAM configuration was the change in the heater power and location on the EECAM. The EECAM heater is located on the exterior side of the mid-section or chassis of the camera housing, as shown in Figure 6, and has a power of 20 W, which is the highest allowable power given the current limit of the switches and camera heater wiring. The difference in the heater designs raises the question of which heater configuration is more thermally robust – resistive heating on the boards or external heating on the housing.

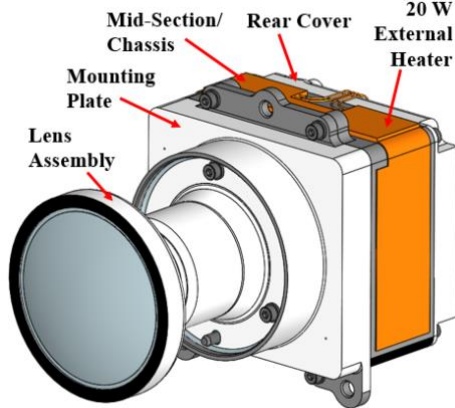


Figure 6 – EECAM (HazCam) Design with Heater

The benefit to using resistive heating on the boards is that the heat is applied directly where it needs to go – to the camera electronics and detector. Since there is less mass that needs to be heated up, the warmup time is faster, less heater power is required, and less energy is consumed. Furthermore, there is a lower heat leak to the environment since a configuration with the heaters on the boards is less susceptible to convective losses to wind. With internal heaters, there is much simpler access to internal wiring and connector pins. In conjunction with the resistive heating, it is necessary that some thermal isolation is applied at the interfaces between the boards and the camera housing to reduce the amount of heat losses from the internal components to the housing during the warmup operation. The eventual problem with this is that the hot-side and cold-side thermal designs are incompatible with one another. Increasing the board-to-housing thermal isolation assists in the WCC warmup but negatively impacts the WCH maximum temperatures since the power-dissipating components on the PCBs no longer have as good of a thermal path to the camera housing, their

primary heat sink. In the reverse, if there were a lower thermal isolation between the boards and housing, then the WCH performance would be benefited but the warmup times and warmup energies would increase. Thus, this heater configuration necessitates an optimized thermal resistance between the boards and housing to minimize heater power, energy, and warmup time while preventing overheating while operating. Furthermore, the resistive heating on the boards does nothing to bring the lens assemblies into their operating temperature ranges – it is likely that the lens assemblies would then require their own external heaters. Accommodation of all the resistors needed to provide sufficient heater power requires a significant amount of board area that is just not available without overwhelming the board area margin (assuming chip resistors are used). Another resistor option is to use Dale Ohm resistors. These resistors have potential for relatively high power dissipations for a small footprint, but their inclusion requires an additional z-height on the boards that is not available inside the camera housing. Finally, with either chip or Dale Ohm resistors, the heat would be entering the board at discrete locations – in order to properly spread the heat across the entirety of the boards, there needs to be sufficient copper content in the PCB layout.

With a heater on the housing, the hot and cold case thermal designs are much more compatible. Increasing the conductance from the boards to the housing helps drive warmup heat into the boards in the cold case and helps drive heat off the boards and into the housing in the hot case. Furthermore, heating on the housing also helps in warming the lenses to their operational temperatures. This configuration does not consume any board area or z-height and decouples the heater design from the electronics design. Additionally, a Kapton film heater can be used to spread the heat across the camera housing mid-section. One of the downsides of this configuration is that the heater is not located where the temperature-sensitive electronics are, resulting in a higher required warmup energy, longer warmup time, and higher required heater power due to the larger mass that needs to be warmed. Since the heater is located externally on the camera housing, there are additional environmental heat leaks due to higher susceptibility to convective heat losses. After examining the pros and cons of each heater configuration, the more thermally robust of the two options is that which has the heater on the housing.

The heaters of the EECAMs are controlled by flight software (FSW) using PRTs (Platinum Resistance Thermometers). For redundancy, in case one fails, there are two PRTs per camera – one A-side PRT and one B-side

PRT. The “A” and “B” sides refer to the respective power modules that the PRTs and heaters are wired to. These modules are called the Rover Power and Analog Modules (RPAMs). Because of the stereo camera pair redundancy in the front HazCams, there is no heater redundancy applied for those cameras. However, since the NavCams, rear HazCams, and CacheCam do not have any camera redundancy, they each have redundant A and B side heaters in place. The front HazCams and NavCams have two cameras per heater switch while the Rear HazCams and CacheCam have one camera per heater switch.

E. Thermal Performance

Table 3 below summarizes the thermal performance characteristics of the EECAMs in the WCC and WCH environments and operational profiles, based on each camera type and each location on the rover.

Table 3 – WCC Warmup Details and WCH Temperatures for each EECAM Type and Location

Camera/Location	WCC, 15 m/sec Wind		WCH, No Wind	
	Warmup Time, minutes	Warmup Energy, W-hr	Max. Camera Housing Temperature, °C	Max. Lens Temperature, °C
Front HazCams	33.7	11.2	35.5	34.6
Rear HazCams	31.8	10.6	34.5	33.7
NavCams	25.9	8.6	25.6	23.8
CacheCam	27.9	9.3	17.1	19.2

The WCC results shown are for forced convection at 15 m/sec wind, conditions which lead to the longest possible warmup times and energies. The camera that experiences the longest warmup time (33.7 minutes) and highest energy (11.2 W-hr) is part of the front HazCam installation. Close behind are the rear HazCams, followed by the NavCams and then the CacheCam. The HazCams generally have longer warmup times than the NavCams (25.9 minutes) and CacheCam (27.9 minutes) since the HazCam lenses are more massive. Although there are differences, all the cameras reach their target temperatures within minutes of one another. Furthermore, the goal of a ~30 minute warmup has been achieved. In comparison, depending on wind speeds, the warmup time of the MSL ECAMs were anywhere between 10 to 15 minutes. Although the warmup times of the EECAMs is about 2x longer than those of the ECAMs, the difference is small enough that mission performance will not be significantly impacted. Even with the significant increase in heater power of the EECAMs over the ECAMs, the energy usage required for a “heat-to-use” tactic will be marginal compared to other rover hardware.

Regarding the WCH performance of the cameras, the hottest camera is one of the front HazCams. Its maximum camera housing temperature is 35.5°C and its maximum lens temperature is 34.6°C. Very close behind are the rear HazCams. It is interesting to note that although the front HazCams are on for two hours at a time and the rear HazCams are only on for five minutes at a time, their maximum operational temperatures aren’t very different. This is because the rear HazCams are located near the MMRTG (see Figure 3), which can potentially operate at temperatures up to 200°C. In comparison, the maximum temperatures of the NavCams (which are also on for 2 hours) are 25.6°C for the camera housing and 23.8°C for the lens assembly. Finally, the CacheCam runs the coolest of all the cameras, since it does not see any sunlight at all and is only on for 20 minutes. Unlike the ECAMs, the EECAMs do not have any operational constraints due to the cameras overheating. As aforementioned, the ECAMs had thermal isolation between the boards and camera housing to help facilitate the WCC warmup, leading to very poor hot side thermal performance. With the change in the thermal architecture, the EECAMs do not have this concern and thus have no AFT violations.

IV. Conclusion

The thermal design of the EECAMs is complete and was successfully presented by the Mars 2020 Flight System Thermal Team in a Detailed Design Review (DDR) in April 2017. With completion of its final reviews, the EECAM team will now commence fabrication, testing, and eventually delivery of the flight hardware. Although the driving design guideline of the Mars 2020 project is to develop a spacecraft that is build-to-print, the new EECAMs deviate from this philosophy. However, all the thermal and mechanical changes that have been made will result in a new camera that will have a significant improvement in optical performance over the MSL ECAMs. Together, these changes have enabled a robust thermal-mechanical design that fits within all the allocated system resources, and is a great improvement over the previous generation of cameras. The next steps in the thermal development are to write

test plans, procedures, and continue analysis for thermal characterization, model correlation, and future LSWs. Afterwards, the team will need to generate heater tables for mission operations.

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References

- ¹Maki, J. N., et al., “Mars Exploration Rover Engineering Cameras,” *Journal of Geophysical Research*, Vol. 108, No. E12, 8071, DOI: 10.1029/2003JE002077, 2003.
- ²Maki, J., et al., “The Mars Science Laboratory Engineering Cameras,” *Space Science Review*, 2012, DOI: 10.1007/s11214-012-9882-4.
- ³Maki, J. N., et al., “Enhanced Engineering Cameras (EECAMs) for the Mars 2020 Rover,” *3rd International Workshop on Instrumentation for Planetary Missions*, Pasadena, CA, October 2016.
- ⁴Farley, K. A., Williford, K. H., “Mars 2020 Landing Site Down-select Feb 2017,” *2020 Landing Site for Mars Rover Mission*, URL: <https://marsnext.jpl.nasa.gov/documents/Mars%202020%20landing%20site%20down-select%20Feb%202017.pdf> [cited 20 April 2017].
- ⁵Hess, S.L., et al., “Meteorological Results From the Surface of Mars: Viking 1 and 2,” *Journal of Geophysical Research*, Vol. 82, No. 28, DOI: 10.1029/JS082i028p04559, 1977.
- ⁶Novak, K. S., Kempenaar, J. G., Redmond, M., Bhandari, P., “Preliminary Surface Thermal Design of the Mars 2020 Rover,” *45th International Conference on Environmental Systems*, Bellevue, WA, July 2015.
- ⁷Johnson, J. R., et al., “Dust coatings on basaltic rocks and implications for thermal infrared spectroscopy of Mars,” *Journal of Geophysical Research*, Vol. 107, No. E6, DOI: 10.1029/2000JE001405, 2002.